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9.5 A TEST OF TWO DISTRIBUTED HYDROLOGIC MODELS WITH WSR-88D RADAR PRECIPITATION DATA INPUT IN ARIZONA

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1. INTRODUCTION AND PURPOSE

Using weather radar for input to distributed hydrologic modeling has drawn considerable interest as computing power, worldwide geospatial data availability, and radar rainfall processing algorithms continue to improve (Tachikawa et al., 2003). The U.S. Bureau of Reclamation (Reclamation) tested two different 2-D distributed-parameter hydrologic models in the case of a heavy rainfall over west-central Arizona. The heavy rain was produced by Tropical Storm Nora, 25-26 September 1997. The primary test area is the Santa Maria basin in West-central Arizona. The two distributed models are GSSHA and *Vflo*™.

The Gridded Surface/Subsurface Hydrologic Analysis (GSSHA) (Downer and Ogden, 2003) is a reformulation and enhancement of the Hortonian runoff model CASC2D (Julien et al. 1995, Ogden 1998). The US Army Research Office and the US Army Corps of Engineers, Engineering Research and Development Center (ERDC) have funded GSSHA development. GSSHA is a square-grid (raster) hydrologic model that solves the equations of transport of mass, energy, and momentum between model cells using a finite difference formulation. Overland and channel flow routing are accomplished using the diffusive-wave approximation of the de St. Venant equations of motion. Infiltration is simulated using the Green and Ampt with redistribution approach (Ogden and Saghafian, 1997). The model is fully unsteady and spatially varied; thus, all model parameters can vary from one cell to the next. The model has been applied to simulate watersheds from 0.016 to 2300 km^2 in area with considerable success (Ogden and Julien, 2002). GSSHA models have been developed with grid sizes ranging from 10 to 1000 m. GSSHA can be run in single event or continuous modes.

GSSHA is capable of simulating both infiltration- and saturation-excess runoff production. The former capabilities are most useful in the case of the Santa Maria watershed. These capabilities are very similar to the predecessor model, CASC2D, with the addition of new solution methodologies that promote model stability. The model has been successfully used to simulate extreme events, return periods greater than 500 years, including the Fort Collins, Colorado, flash flood of 1997 (Ogden et al. 2000), and the Rapidan Flood (Virginia) of 1995 (Landel et al. 1999).

Vflo is a real-time distributed hydrologic model for managing water resources, water quality management, and flood warning systems. Distributed hydrologic modeling capitalizes on access to high-resolution quantitative precipitation estimates from model forecasts, radar, satellite, rain gauges, or combinations in multi-sensor products. Digital maps of soils, land use, topography and rainfall rates are used to compute and route rainfall excess through a network formulation based on the Finite Element Method (FEM) computational scheme described by Vieux (2001a, and 2001b). *Vflo* is a new model implemented in Java™ to take advantage of secure servlet/applet technology for multi-user access. Vieux and Vieux (2002), describe the *Vflo* model in more detail which was first deployed in 2001 in the Salt and Verde watersheds for the Salt River Project, Arizona.

The overall goal of *Vflo* is to provide high-resolution, distributed hydrologic prediction from catchment to river basin scale. The advantage of physics-based models is that they can be setup with minimal historical data and still obtain meaningful results. Distributed models better represent the spatial variability of factors that control runoff enhancing the predictability of hydrologic processes (Vieux, 2002). Finite element solution of the kinematic wave equations is an efficient approach allowing large systems to be solved easily on single processor Intel PC's in a Windows environment, or on servers. *Vflo* is set up using a drainage network rather than a basin approach. Solution proceeds on a drainage-network basis making the same model scalable from small catchment to major river basin. Channel routing through measured cross-sections, reservoirs, and looped rating curves extend the applicability to larger river systems. Operational flood forecasting is supported by continuous simulation of soil moisture, and both infiltration and saturation excess runoff processes. Inputs include multiple sensors including radar, satellite, and rain gauge. Calibration is accomplished using the Ordered Physics-based Parameter Adjustment method described by Vieux and Moreda (2003). Often, no calibration is needed except for minor adjustments to initial values derived from published characteristics of soils and vegetative cover (Vieux, 2001a). Vflo represents an important advance in simulating rainfall-runoff in real-time using digital data describing the Earth's terrain coupled with advances in radar precipitation detection.

We plan to integrate a distributed hydrologic model such as GSSHA or *Vflo* into a generalized watershed management framework, such as the

RiverWare modeling tool (Zagona et al. 2001) currently used by Reclamation. RiverWare is a water resources management tool for operations, scheduling and planning, which builds water operations models and applies decision criteria to them. This integration may be considered analogous to the relationship of CASC2D to WMS.

Both distributed models require Geographic Information Systems (GIS) data as input, such as basin definitions, topography, soils and land use data. The following section will detail these GIS data.

2. GIS DATA INPUT

Distributed hydrologic models may require slightly different inputs and formats, but most need the same basic ingredients. Basin delineation, channel network delineation, overland flow slope, flow accumulation and drainage direction are all derived from topographic data, typically in the form of a Digital Elevation Model (DEM). Digital soil surveys may supply soil infiltration parameter estimates, and digital maps of land use/cover are generally used as the basis for estimates of surface hydraulic roughness coefficients. Arguably the most critical component is a temporally and spatially variable precipitation field. In distributed hydrologic models, such variability is accommodated by the model's spatially variable characteristics within an individual basin, derived from the aforementioned GIS input. Other factors such as temporal and spatial resolution of the input data and transformation of those data into parameters usable by the model are also crucial considerations in the modeling process.

For this preliminary comparative study, while both GSSHA and *Vflo* have some flexibility as to the format of GIS data that they will accept, the most important requirement of this test is that they operate from the *same* input data set. This stipulation allows for a valid comparison of the models themselves instead of the quality of their input data. From these basic data sets, the specific model parameters and inputs will be derived for the respective models. The following data sets were selected for the comparison:

- DEM data with 30 m horizontal resolution from the U.S. Geological Survey (USGS) EROS Data Center's National Elevation Dataset (NED).
- Land Use Land Cover data at 30 m resolution, from the USGS EROS Data Center's National Land Cover 1992 Dataset (NLCD).
- Soil data from the Natural Resources Conservation Service State Soil Geographic (STATSGO) database for Arizona.

GIS data coverages for GSSHA were input using the Watershed Modeling System (WMS) hydrologic model interface, which was developed at Brigham Young University in cooperation with the U. S. Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory.

Channel cross-section surveys are important to accurately quantify channel geometry for flow calculations. Unfortunately, only one surveyed cross-section, at a stream gauge location on the Santa Maria River, is available. The fluvial geomorphology in the Santa Maria catchment is typical of steep arid watersheds in the western U.S. The channels are wide, with braiding tendencies and plane beds. Thus, in GSSHA the channels were modeled as trapezoidal cross-sections with channel widths estimated from aerial ortho-photographs from http://terraserver.microsoft.com. Similar scaling from aerial photos was accomplished for Vflo.

3. RADAR DATA INPUT

Radar data input was from the WSR-88D (formerly NEXRAD) Doppler radar (Crum et al. 1993) south of Flagstaff, Arizona (KFSX), which is about 150 km east of the headwaters of the test basin. The data consist of reflectivities in Level II format from the National Climatic Data Center, which have a data resolution of 0.5 dB. The beam width at the headwaters range is about 3.6 km and the lowest (0.5°) beam center altitude is about 3.4 km above ground level (Fig. 1). This location is considered to be at moderate range from the radar for precipitation estimation in the warm September atmosphere over Arizona.

The radar quantitative precipitation estimation (QPE) was accomplished via use of Reclamation's new Precipitation Accumulation Algorithm (PAA; Hunter et al. 2001). The PAA uses Eta model soundings to distinguish rain, snow, melting snow, and virga regions and applies different Z-R relationships to each, producing precipitation accumulations at the surface. In this case, the National Weather Service (NWS)-sanctioned *tropical* Z-R relationship ($Z = 250\ R^{1.2}$) was used for all precipitation, since its phase was all liquid at the surface and was produced by a tropical storm. Finally, a single precipitation gauge/radar QPE bias (G/R) for the entire radar umbrella was calculated from all available G/R pairs. Most of the gauge data were 24-hour accumulations from NWS cooperative observers, but a few were from METAR reporting sites near airports. These steps optimized the accuracy of the precipitation field. This field was converted to a 1 km geo-referenced grid for incorporation into the hydrologic models.

4. TEST CASE DESCRIPTION

4.1 Santa Maria Basin

The Santa Maria basin is an unregulated headwater basin in West-central Arizona, flowing from elevations over 2 km west of Prescott toward the Bill Williams River at Alamo Lake, in the lowland desert of western Arizona. The Bill Williams River discharges into the mainstem of the Lower Colorado River near Lake Havasu City. The area of the Santa Maria basin is

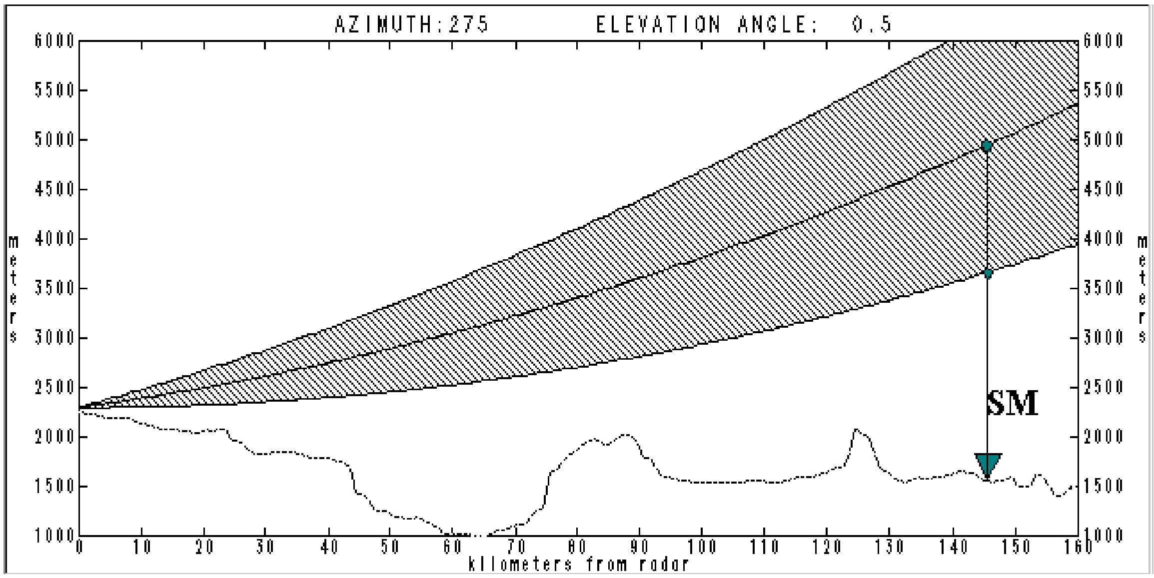

Figure 1. Representation of lowest (0.5° elevation) radar beam extent from Flagstaff AZ WSR-88D (KFSX) along azimuth 275°, which lies over the headwaters of the Santa Maria (SM) test basin. Arrow denotes location of aforesaid headwaters and line and circles above the arrow designate beam heights and width above this location (see text).

3,727 km^2. Figs. 2 and 3 show the location, hydrography and topography of the region surrounding the basin. As would be expected for the arid desert soils and steep topography of this basin, response times in the event of heavy rains are small. While the Santa Maria not a sidewash basin directly upstream from the Lower Colorado River, it is close to that river (Fig. 3) and has similar desert soil characteristics to the sidewash basins of concern. The Santa Maria River, as noted previously, flows into the Bill Williams River. The Bill Williams basin is therefore a potential major contributing inflow to the Lower Colorado. We chose not to make that our test basin because Alamo Dam regulates it in flood control situations, thus making basin flows difficult to simulate using the distributed models.

An encircled red dot in Fig. 2 indicates the single active stream gauge in the basin, namely USGS 09424900 on the Santa Maria River. The elevation of this gauge is 415 m above sea level and is 17 km above the basin outlet, with a drainage area of 2,924 square km. Mean annual streamflow at the gauge varies widely from year to year - from 1967 to 1999 values ranged from zero to 6.6 cubic meters per second (cms), with an average of 1.9 cms. On many days in most years there is no flow. The same large variability is also evident in annual *peak* streamflows, which are presented in Fig. 4.

4.2 Synoptic and Hydrologic Characteristics of the Storm

Tropical cyclones are rare in Arizona, but occur occasionally as they make landfall from the eastern Pacific or Gulf of California. Tropical Storm (TS) Nora was an example of the latter landfall location. TS Nora's center traveled along the western Gulf of California and accelerated northward at landfall, which was near the California/Arizona border at 2100 UTC 25 September 1997 (Fig. 5 and Rappaport 1997). The most recent precipitation in the region prior to the 25th was nine days earlier, so soil conditions were dry. At that time most of the heaviest precipitation was occurring to the northeast of Nora's center, in Arizona. The storm rapidly weakened after that time and by 0000 UTC 26 September TS Nora was downgraded to the Tropical Depression category (maximum sustained surface wind speed 17 m s-1 or less), when its center was near Parker, Arizona (PRKR in Fig. 3). Despite this weakening, Nora produced very heavy rain in and near the Santa Maria basin on both the 25th and 26th. While approximately 2-10 mm of precipitation fell in the headwaters of the basin from 1200 UTC on the 24th to 1200 UTC on the 25th, much greater amount occurred the following day, from 1200 UTC on the 25th to 1200 UTC on the 26th. An isohyetal analysis for the latter period is given in Fig. 6. Northward-flowing tropical moisture intercepted the elevated terrain in the headwaters (eastern and northern) portion of the basin (Fig. 3), and this upslope flow undoubtedly enhanced precipitation in those areas. This notion is supported by the highest recorded rainfall from this storm (305 mm/24 hr, an unofficial state record), which was in the Harquahala Mountains, 16 km southwest of Aguila (AGLA) in Fig.3 (off the map). These mountains form an isolated southwest-northeast oriented range, with a peak elevation of 1.74 km. This orientation was optimal for barrier-perpendicular upslope flow.

Cushmeer (1999) performed an in-depth analysis of the performance of the WSR-88D at Yuma, Arizona (KYUX) during the TS Nora event. This analysis was focused on southwest Arizona, to the south of our study area. Nevertheless, this paper revealed that there was considerable underestimation

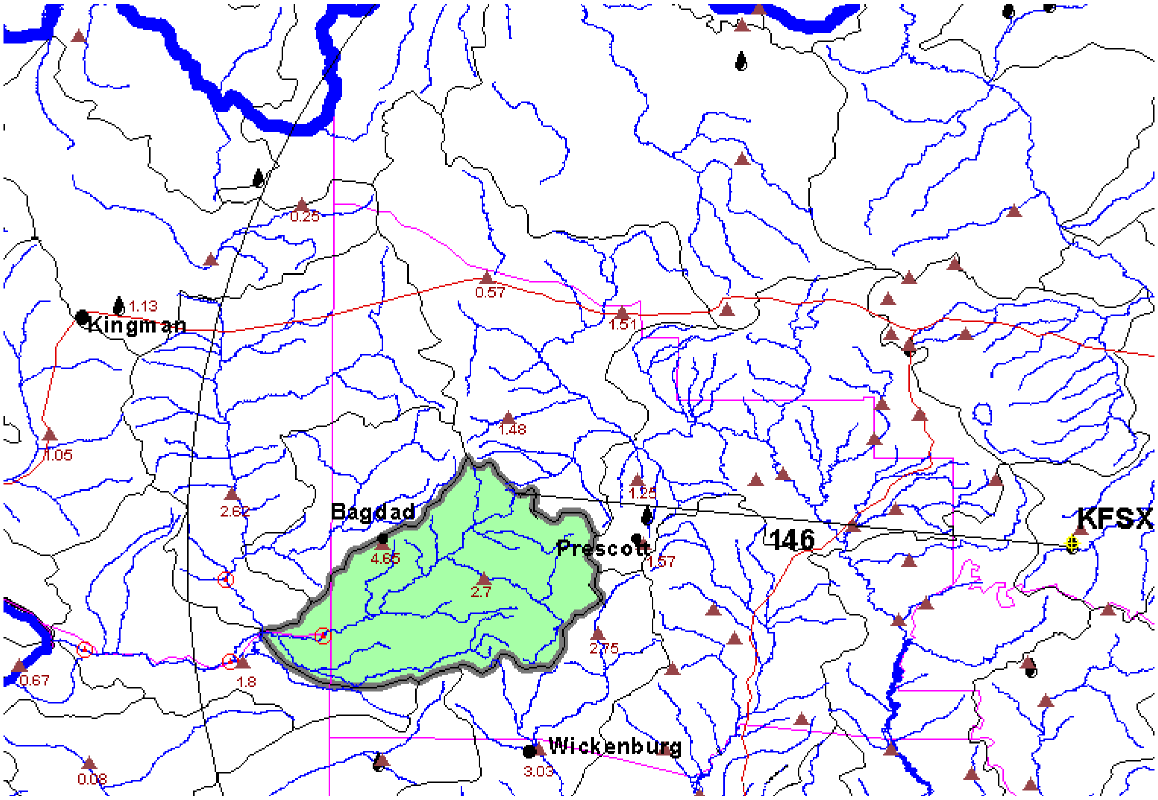

Figure 2. Map of the region surrounding the Santa Maria test basin, which is highlighted in green. Brown triangles show locations of NWS Cooperative Observing sites. Those sites with numbers underneath the symbols show active reporting sites during this event; the numbers themselves indicate 24 hour precipitation from 1200 UTC 25 September 1997 through 1200 UTC 26 September 1997. Red encircled dots pinpoint USGS streamflow gauges that report in real time. Purple lines outline counties, red lines interstate highways, and black lines other basins. The black droplet symbols show other precipitation reporting stations. The straight black line connects the KFSX radar and the headwaters of the Santa Maria basin, with the line distance indicated in km. The Colorado River is shown by the thickest blue streamlines on the western and northern fringes of the figure.

of radar QPEs by the WSR-88D's Precipitation Processing Subsystem (PPS) for the tropical precipitation in the western third of the state. This underestimation occurred despite application of the NWS tropical Z-R relationship, which is intended to diminish underestimation by the default Z-R relationship (Z = 300 R1.4) that is normally in effect. The author cited drop breakup into small drops with low reflectivities as a likely cause for the underestimation. In this study we intend to apply the tropical relationship as a starting point for the KFSX QPEs, but we will use Reclamation's PAA (with G/R bias) rather than the PPS estimates for more accurate precipitation input.

Flooding, flash flooding and urban flooding occurred in and near Bagdad, Prescott, Aguila, and north of Wickenberg. The flooding and rock or mudslides closed several roads in and around these communities on the 25th and 26th. The flooding at Aguila was aided by the bursting of an earthen dike. The daily *mean* flow at the Santa Maria River gauge increased from zero on the 24th to 2 cms on the 25th to 54 cms on the 26th. Apparently the gauge either malfunctioned or was swept away by the river after that, as the discharge had to be estimated by the USGS for the next four days (the estimate was 12.7 cms on the 27th). The stream gauge on the Big Sandy River (USGS 09424450, labeled BS in Fig. 2) reported a daily mean discharge of 99.4 cms on the 26th.

5. HYDROLOGIC MODEL CALIBRATION

As with any hydrologic model, calibration is essential. Unfortunately, in this desert region of Arizona, there are few stream gauges offering past data on which to calibrate. Runoff in the Santa Maria catchment is thought to be almost entirely generated by the infiltration-excess mechanism, so neither model included return flow to the channel. The number of grids used to describe a basin in either hydrologic model is a function of the grid size used in the model. Simulation times depend to a great extent on the number of grids. Selection of a grid size is a function of both run time

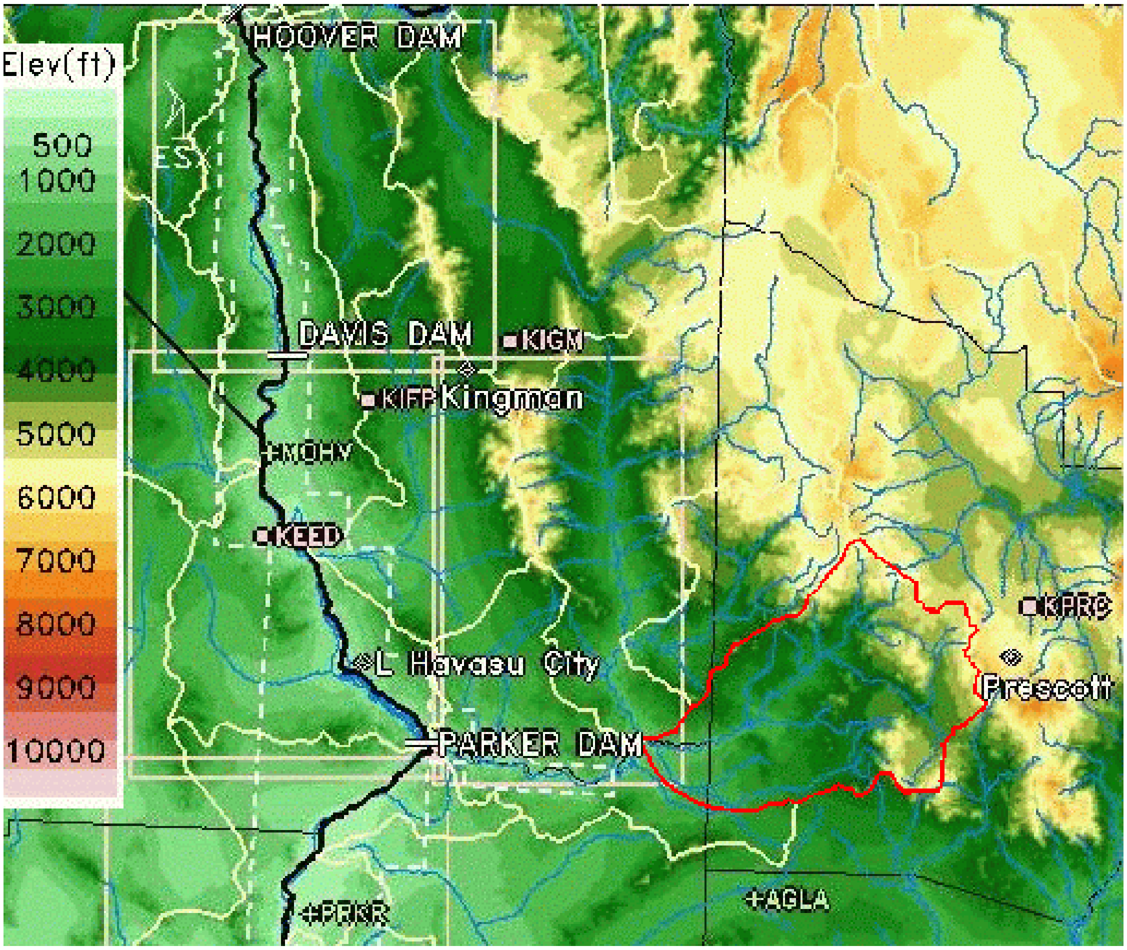

Figure 3. Topographic map of region surrounding Santa Maria basin, which is outlined in red. Color scale for elevations (in feet) is at left. State boundaries are thick black lines and county lines are thin black. Other (USGS 8-digit HUC) basin boundaries are in yellow.

constraints and the level of detail required to describe the spatial variability of watershed characteristics. GSSHA model parameter space was fully explored by an automated calibration procedure - the Shuffled Complex Evolution (SCE) optimization method (Duan et al. 1992). The SCE method was developed specifically for the automated calibration of lumped parameter hydrologic models. However, Senarath et al. (2000) demonstrated that it has utility for calibrating distributed hydrologic models as well, provided that parameters are assigned based on indices. The SCE method requires the computation of a cost function; the hydrograph Root Mean Square Error (RMSE) was subjectively used as a goodness of fit indicator.

Vflo™ calibration is adjusted following the OPPA method. Limited sensitivity studies in this watershed and others reveal that model response is sensitive to channel characteristics governing the hydraulics of the channel flow routing. The overland and channel parameters governing infiltration and hydraulic roughness are adjusted by applying scalar multipliers to the initial values derived from soils and landuse/cover to achieve an overall match between the hydrograph, shape, timing, and peak. For predicting flood response from basins and impacts of sidewash sediment transport, the rate of rise of the rising limb is an important indicator of whether the model physics and calibration provide an adequate forecast tool. The preliminary results from both models in terms of time trials and hydrograph simulations are presented below.

5. TEST RESULTS

As stated earlier, we ran both GSSHA and *Vflo* with identical GIS and radar QPE data input for this test case. This will enable a fair comparison of the performance of the two models in the arid and topographically complex Santa Maria basin of western Arizona. The two main objectives for this test were: 1) To assess if the models run sufficiently fast so as to produce output in near-real-time and 2) to see which model provides the more accurate stream flow

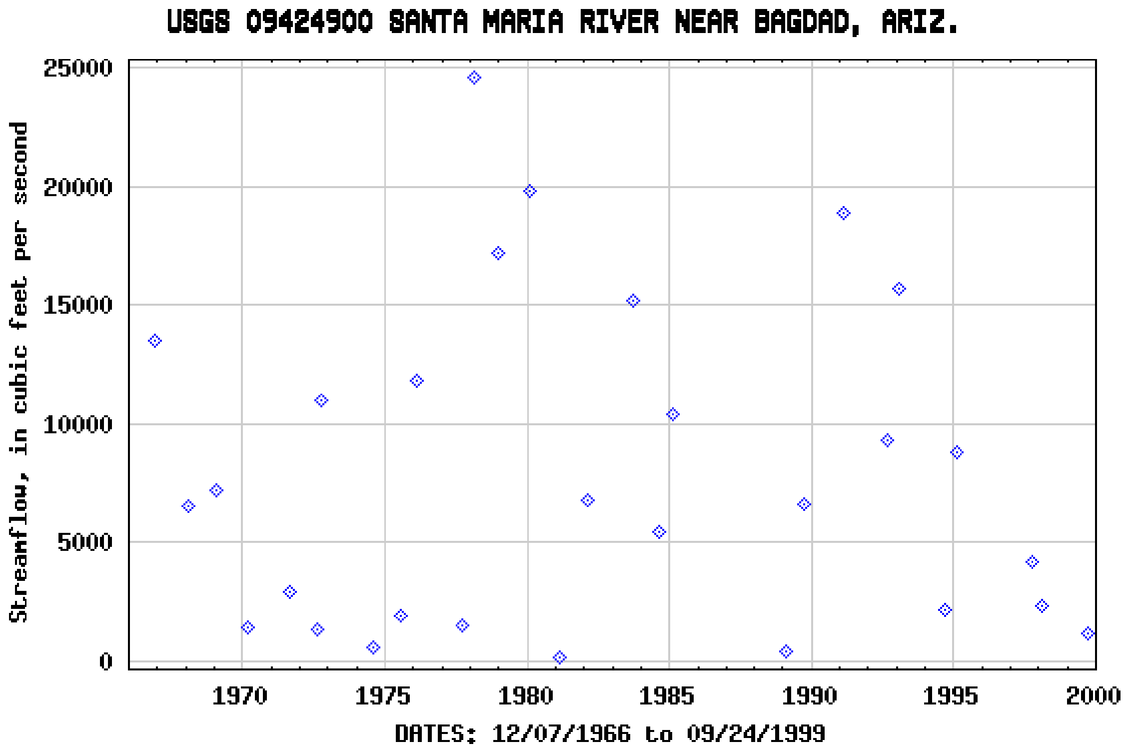

Figure 4. Peak streamflow for each year at the Santa Maria stream gauge for the given period of record. Courtesy U.S. Geological Survey.

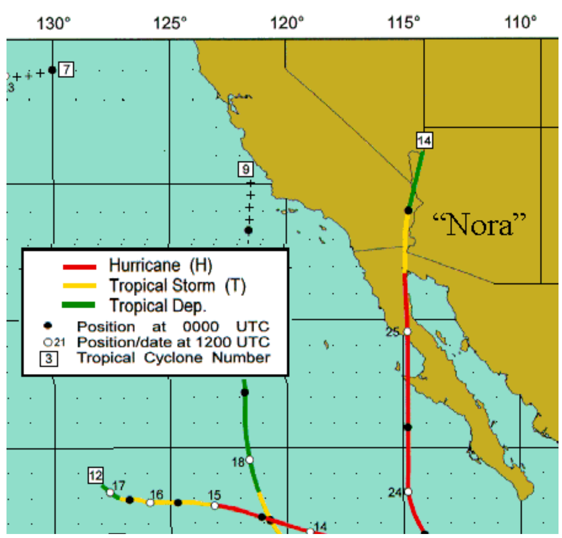

Figure 5. Track of tropical cyclone Nora, with strength categories and positions as indicated in legend. Nora is number 14. Courtesy National Hurricane Center.

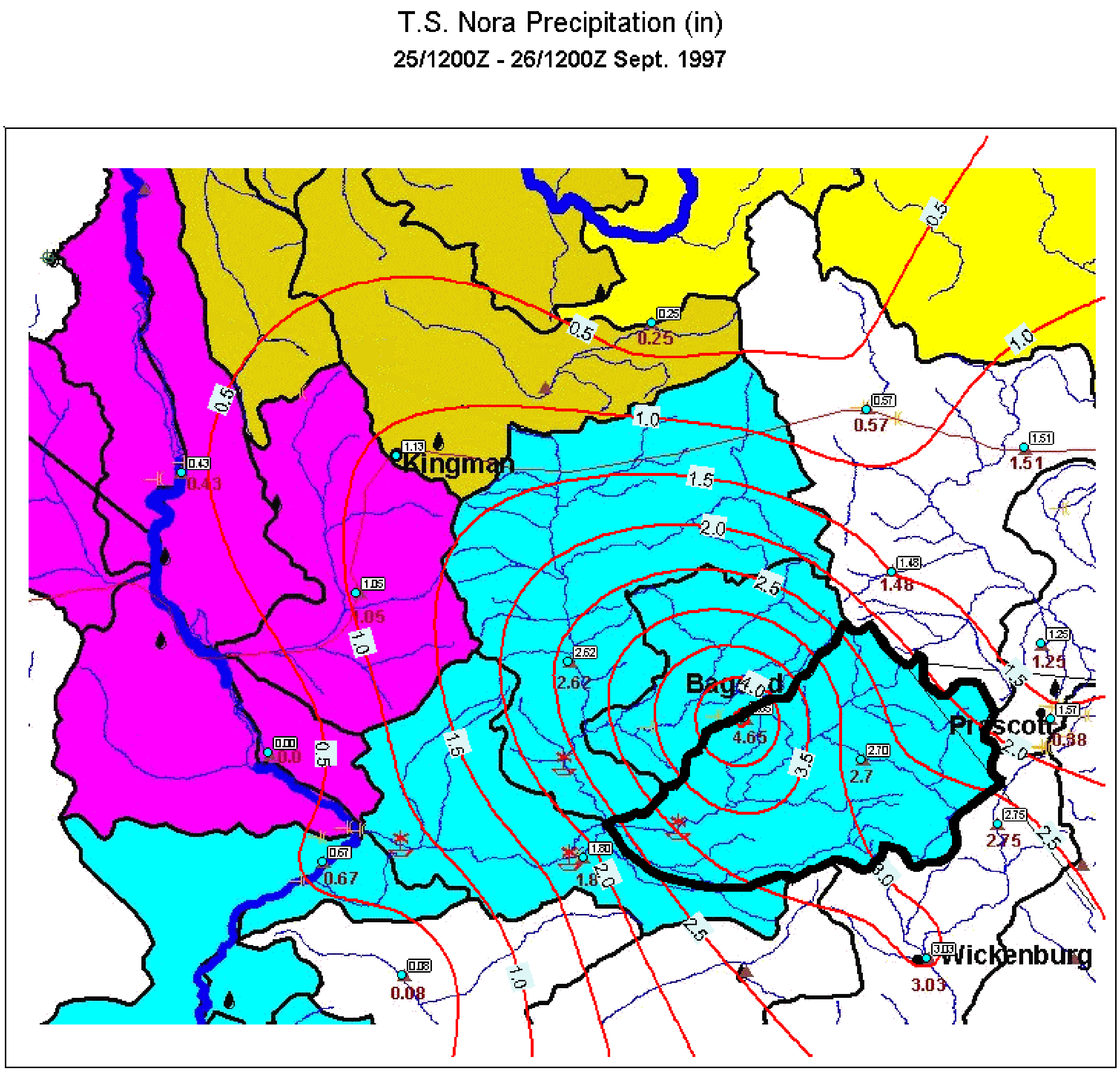

Figure 6. Isohyetal analysis (red contours) of rainfall amounts in inches (brown values), for period specified in title. Precipitation gauge data for analysis are from all available reporting sites (brown triangles and drop icons, as in Fig. 2). Heavy black line envelops Santa Maria basin. Red icons with asterisks are active stream gauges, as in Fig. 2.

hydrographs when compared to the USGS stream gauge data. To accomplish the latter, we tried to use not only the Santa Maria River gauge but also one on the Big Sandy River near Wikieup. The Big Sandy is also an unregulated basin and is considered a backup to the Santa Maria for this test. As seen in Fig. 2, the cooperative observing site just north of the Big Sandy stream gauge reveals that heavy rain also fell in this basin (66.5 mm in 24 hours ending 1200 UTC on the 26th).

The time it takes a distributed hydrologic model to execute a simulation is as important as the accuracy of its output hydrographs because of our intended application for the model. This ultimate desired application is the coupling of a distributed model with a "live" WSR-88D data feed for near-real-time hydrographs of sidewash inflows to the Lower Colorado River, for operational use. Heavy sidewash inflows can occur with widespread rainstorms such as tropical cyclones and cause unexpectedly high water volumes on the Colorado mainstem. These volumes pose a problem for Reclamation's water management in the numerous reservoirs along the mainstem. It may even cause flooding, especially in the normally low water, flood control season from January through July. Rapidly updating hydrographs produced by a distributed model, which is capable of ingesting new WSR-88D radar volume scans every 5 or 6 minutes, would provide tremendous decision assistance to Reclamation's water managers in the effective release of water from dams. Such a system could easily be transported to other regions of the United States, since radar input would be available from the operational WSR-88D network deployed throughout the country.

Testing of the Vflo model show that for 81 hours of simulation to analyze the cell located at the Santa Maria stream gauge site, the CPU time at 200 m resolution was 146 seconds; for 500 m resolution the CPU time was 24 seconds. These results were obtained on a dual-processor personal computer (PC) with an Intel® Pentium® III chip, 1.27 GHz clock speed, 2.4 Gb RAM, and MS Windows® 2000 operating system (OS). On a single-processor PC with 1.8 GHz clock speed, 0.5 Gb RAM and a Pentium® IV chip, the 500 m resolution run took 17 seconds of CPU time. Clock speed appears to be the dominant hardware factor affecting simulation time with Vflo.

At 500 m grid size, GSSHA simulates the extreme flood event in slightly less than 25 seconds on a faster clock speed of 1.8 GHz AMD Athlon computer with 512 MB RAM. At 200 meter resolution, GSSHA took 167 sec. Table 1 summarizes the simulation time for both models at the two resolutions for a simulation period normalized to 81 hours.

Table 1 Simulation Time Santa Maria Basin

	Resolution / # grid cells	
Model	**200-m / 73,250**	**500-m / 11,738**
Vflo	146 sec	22 sec
GSSHA	167 sec	30 sec

Both models ran in less than 30 seconds for one medium-sized basin. Along the Lower Colorado reservoir system, however, problems in handling water volume normally arise when multiple sidewash basins are in flood. So, while there is not a precisely linear relationship between modeled area (and number of grid points), we linearly extrapolated the Santa Maria CPU times to all the adjacent sidewash basins from the Grand Canyon to Mexico (Fig. 7). This was done to obtain a rough estimate of a worst case widespread flooding situation, one that is unlikely to occur. Nevertheless, despite over 105 grid cells for 500 m resolution across this large area, estimated run times were 1.3 and 0.94 minutes for GSSHA and Vflo, respectively. Therefore we conclude that both models run fast enough to provide real-time decision support to water operations along the Lower Colorado.

The simulated vs. gauge hydrographs are shown in Fig. 8a and 8b for GSSHA and V*flo*, respectively. models replicated the largest peaks in the gauge hydrograph fairly well. On another optimistic note, neither model showed significant differences in hydrograph response between runs at 200 m and 500 m resolutions. Therefore, 500 m grid size will probably be adequate for future simulations, reducing CPU times.

6. CONCLUSIONS AND PLANS FOR FURTHER RESEARCH AND APPLICATION

The test results are encouraging for integration of real-time, radar QPE-fed, hydrologic modeling system for decision support in water operations management. Both models were sufficiently fast with readily available computing capabilities to produce timely outputs. Both models were capable of simulating the observed hydrograph as shown in Figs. 8a and 8b. Vflo ably reproduced the multiple peak and rising/recession limbs, while GSSHA simulated the two largest peaks well. Further calibration will refine results from GSSHA and Vflo.

Since the accuracy of any distributed hydrologic model is dependent on the input precipitation field, Reclamation continues to seek improvements to radar QPEs. The PAA represents a major progression toward that end, but the algorithm is still under testing and development. We are currently engaged with the National Severe Storms Laboratory to develop and test a version of their Quantitative Precipitation Estimation and Segregation Using Multiple Sensors (QPE-SUMS) system (Gourley, 1998; Gourley et al. 2001), which is also operating in Arizona. We intend to test both the PAA and QPE-SUMS in the hope to obtain the best possible radar QPE input for whatever distributed hydrologic model is implemented operationally as a water management tool. A key need of operational hydrologists is data processing within a decision support system (DSS). The WMS hydrologic model interface provides an excellent front-end for model set up, but is not intended to provide decision support capabilities. The outputs from GSSHA and Vflo are, however, suitable for use in a DSS. Future plans call for integration of the selected QPE-fed model with the RiverWare DSS. The first step toward this incorporation will be done as part of Reclamation's AWARDS/ET Toolbox system (Hartzell et al. 2000).

The current GSSHA development effort is aimed at incorporating lakes, reservoirs, wetlands, and detention basins. These additions will allow complete simulation of large watersheds with diversions, reservoirs with scheduled releases, rule curves, and arbitrary release schedules. This version of GSSHA will be completed in the summer of 2003. Researchers at the University of Connecticut are also working to refine the sediment source terms used in the GSSHA overland erosion component. Vflo already has a module to simulate reservoirs, with rule curve functionality. Water dispatch, diversions, and reservoir releases will be added later. A snowmelt module in Vflo is being tested for the Salt River Project watersheds.

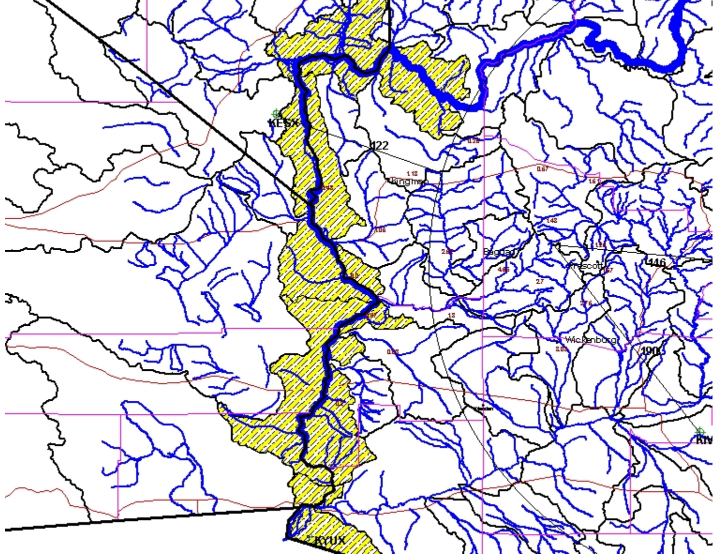

Figure 7. Map with sidewash basins highlighted that were selected for “worst case” flood, for extrapolation of model time trial results on Santa Maria basin.

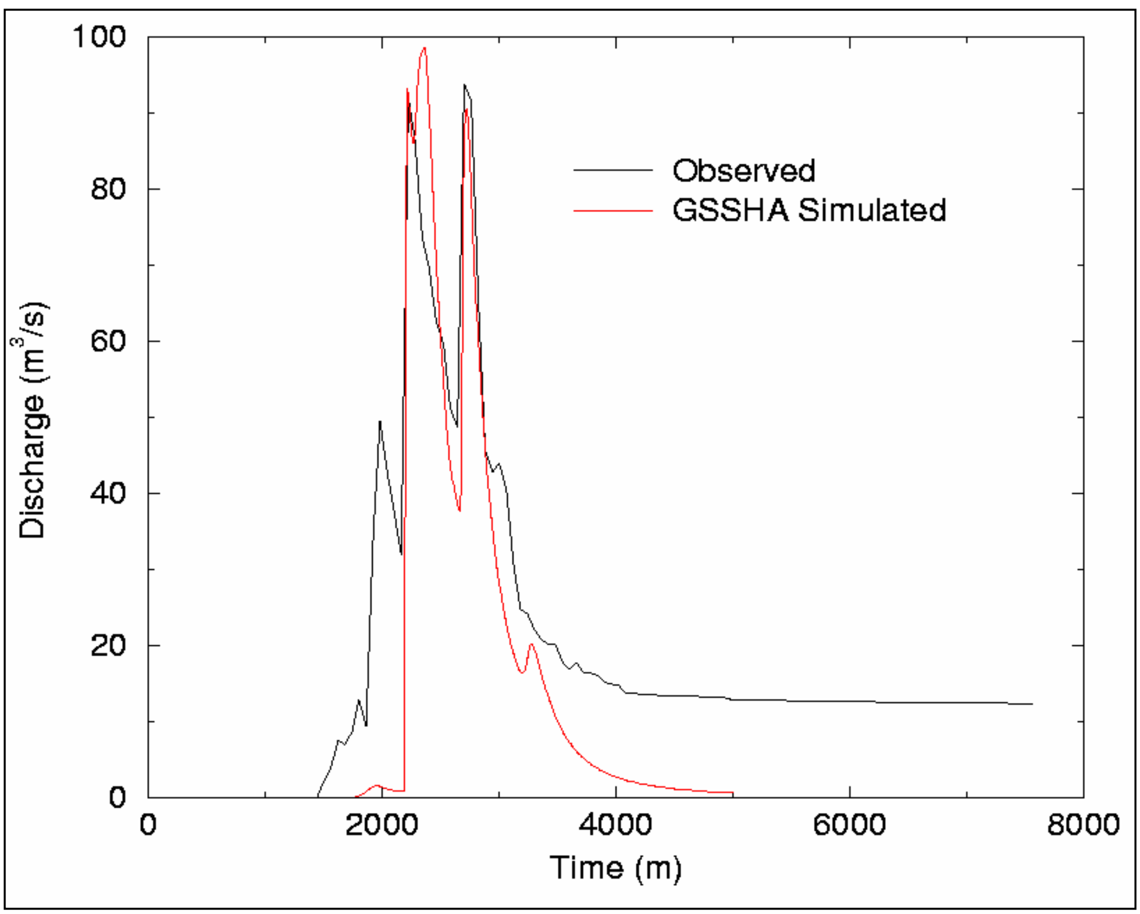

Figure 8a. GSSHA-simulated hydrograph at Santa Maria gauge location. The observed hydrograph from the USGS gauge itself is the black line and the hydrograph modeled by GSSHA is the red line.

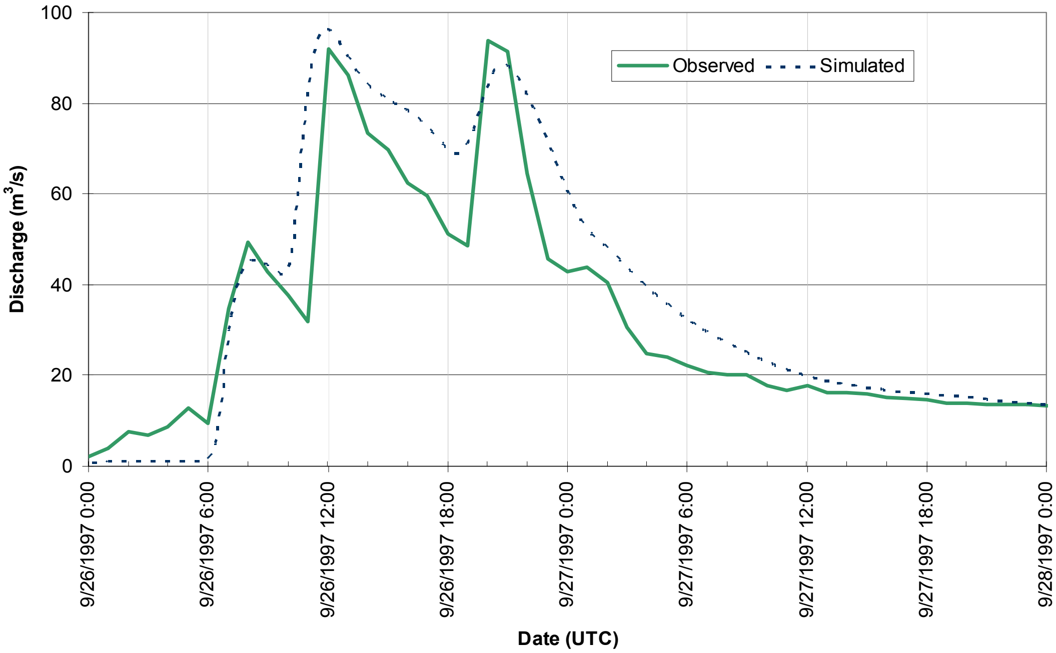

Figure 8b. Vflo™ simulated hydrograph showing match between rising limb, multiple peaks and recession limb.

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